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(71) Applicant *(for all designated States except US)*: AMATI COMMUNICATIONS, INC. [US/US]; Suite 303, 1975 El Camino Real West, Mountain View, CA 94040 (US).

(72) Inventor; and
(75) Inventor/Applicant *(for US only)*: CIOFFI, John, M. [US/US]; 7879 Creekline, Cupertino, CA 95014 (US).

(74) Agents: HICKMAN, Paul, L. et al.; Hickman & Beyer, P.O. Box 61059, Palo Alto, CA 94304 (US).

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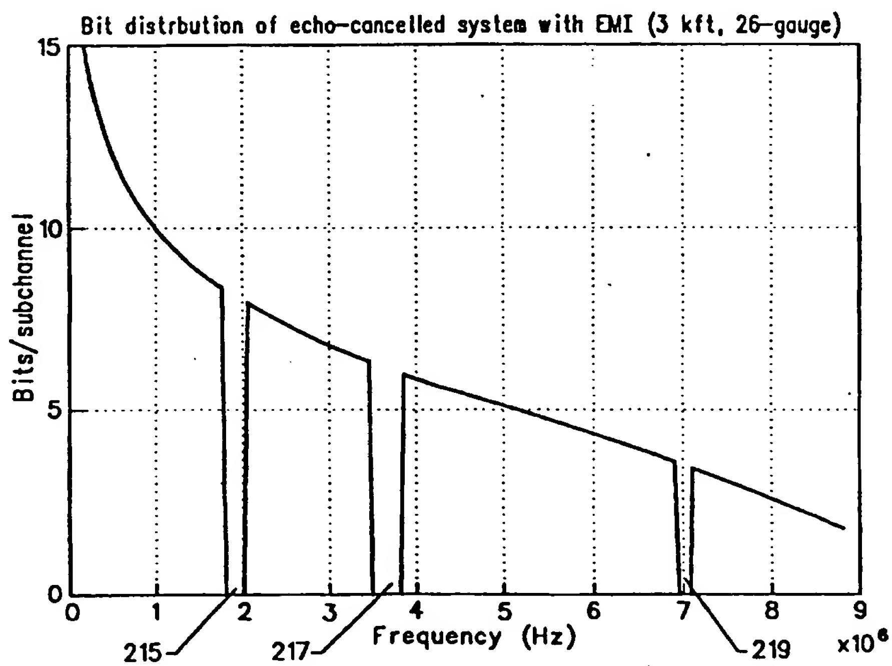
(57) Abstract



A transmission scheme contemplates encoding and modulating digital data onto a discrete multi-tone signal having a total banwidth of at least 1.6 MHz. The modulation system dynamically updates the subcarriers used and the amount of data transmitted on each subcarrier during transmission (215, 217, 219). In one embodiment, the multi-tone encoding and modulation complies with the ATIS North American Asymmetric Digital Subscriber Lines standard. However, additional subchannels (a total of 512) and/or subchannel bandwidths of greater than 4.3125 kHz may be used. In this system, the subchannels occurring above frequencies set forth in the standard are treated similarly to those within the standard range in terms of subcarrier selection criteria. This system permits transmission of digital data at transmission rates of 6-55 Mbps over twisted pair lines at distances of 1200 meters on lines experiencing significant crosstalk noise such as T1 or E1 (215, 217, 219), as well as at transmission rates of 10-50+Mbps over distances of 2000 meters.

IMPROVED ADSL COMPATIBLE DISCRETE MULTI-TONE APPARATUS

BACKGROUND OF THE INVENTION

The present invention relates generally to systems for the transmission and reception of multi-carrier, high speed data signals. More particularly, a discrete multi-tone (DMT) system having a widened bandwidth is described.

At the time of this writing, the Alliance For Telecommunications Information Solutions (ATIS), which is group accredited by the ANSI (American National Standard Institute) Standard Group, has finalized a standard for the transmission of digital data over Asymmetric Digital Subscriber Lines (ADSL). The standard is intended primarily for transmitting video data over ordinary telephone lines, although it may be used in a variety of other applications as well. The standard is based on a discrete multi-tone transmission system. Transmission rates are intended to facilitate the transmission of information at rates of at least 6 million bits per second (i.e., 6+ Mbps) over ordinary phones lines, including twisted-pair phone lines. The standardized discrete multi-tone (DMT) system uses 256 "tones" that are each 4.3125 kHz wide in the forward (downstream) direction. That is, in the context of a phone system, from the central office (typically owned by the telephone company) to a remote location that may be an end-user (i.e., a residence or business user).

The Asymmetric Digital Subscriber Lines standard also contemplates the use of a duplexed reverse signal at a data rate of at least 608 Kbps. That is, transmission in an upstream direction, as for example, from the remote location to the central office. Thus, the term Asymmetric Digital Subscriber Line comes from the fact that the data transmission rate is substantially higher in the forward direction than in the reverse direction. This is particularly useful in systems that are intended to transmit video programming or video conferencing information to a remote location over the telephone lines. By way of example,

multi-tone technology. The present invention is believed to be one solution to the crosstalk noise problem. The described solution is equally applicable to phone systems that experience E1 noise (which are primarily located outside of North America), although the problem is more pronounced in areas that experience T1 crosstalk noise.

The present invention also provides a solution that has numerous advantages well beyond the mitigation of crosstalk noise problems. For example, in areas which are not susceptible to T1 or E1 crosstalk noise (which is the vast majority of the installed telephone system base), the described invention permits reliable transmission of digital information at rates of 10-50 Mbps per second or greater over installed lines. The system also permits a provision for higher speed transmissions in the upstream direction. As will be appreciated by those skilled in the art, these transmission rates are substantially greater than those that are currently obtainable.

SUMMARY OF THE INVENTION

In view of the foregoing, it is an object of the present invention to provide a method of transmitting digital information from a source over a potentially noisy subscriber communication line using a discrete multi-tone transmission scheme. The system contemplates encoding digital data and modulating the encoded data onto a discrete multi-tone signal having a total bandwidth of at least 1.6 MHz. In some embodiments, bandwidth of more than 8 MHz are used. The communication line is monitored to determine at least one line quality parameter including noise levels at each of a multiplicity of subchannels that each correspond to an associated subcarrier tone. The modulation scheme is arranged to take into consideration various factors including the detected line quality parameters, subchannel gain parameters, and a permissible power mask parameter when modulating the discrete multi-tone signal. The modulation system is also capable of dynamically updating the subcarriers used and the amount of data transmitted on each subcarrier during

In another application of the invention, it may be used with ordinary telephone lines such as twisted pair lines to transmit data to remote receivers located up to 2000 meters from the transmitter at digital data transmission rates of at least ten million bits per second (10 Mbps). Indeed data transmission rates of in excess of 25 Mbps at distances of 1000 meters and 50 Mbps at distances of 600 meters of twisted pair lines are readily obtainable.

In another application of the invention, additional bandwidth may be made available for upstream communications to permit upstream communication at any desired data rate.

DETAILED DESCRIPTION OF THE INVENTION

The presently proposed ATIS Asymmetric Digital Subscriber Line North American standard contemplates use of a Discrete Multi-Tone (DMT) data transmission scheme. A detailed description of the protocols for the Discrete Multi-Tone transmission scheme is described in detail in the pending North American Standard, which is referred to as the T1E1.4 ATIS Standard, and is presently set forth in Standard Contribution No. 94-007, rev. 8, dated March of 1995. As illustrated in Figure 1, the standardized discrete multi-tone (DMT) system in North America uses 256 "tones" which are each 4.3125 kHz wide in the forward (downstream) direction. The frequency range of the tones is from zero to 1.104 MHz. The lower 32 tones may also be used for duplexed data transmission in the upstream direction. As described in the background section of the application, one acknowledged limitation of the discrete multi-tone transmission system that has generally been thought of as being unsolvable is reliable carrier service area signal transmission in the presence of T1 crosstalk noise.

The solution proposed herein is significantly increasing the transmission bandwidth. In one example, this is done by increasing the number of subchannels, with each subchannel having the same width. In another example, this is done by increasing the bandwidth of each subchannel. That is, instead of the 256 subchannel 1.104 MHz bandwidth set forth in the proposed standard (which is seen in Figure 1), a system having on the order of two to ten times that bandwidth is proposed. By way of example, in one embodiment, the transmission bandwidth is doubled by providing 512 subchannels each having a 4.3125 kHz width to provided a total 2.208 MHz bandwidth. In another embodiment, eight times as many 4.3125 kHz wide subchannels are used to provide an 8.832 MHz bandwidth. When desired, the number of subchannels (and therefore the bandwidth) available for upstream transmissions may also be increased. The bandwidth allocated to upstream transmission may be widely varied to meet the needs of any particular application. By way of example, the number of subchannels available for upstream

shows the number of bits carried on each tone for a one kilometer 26 gauge phone line with worst-case crosstalk. The margins in this case are approximately 12.4 decibels, which is well above the margins that are generally considered necessary for digital data transmission (minimum margins of about 6 decibels are typical.) As can be seen in the graph, there is significant data transmission at frequencies above 1.1 MHz.

Referring next to Figure 3, the described system's usefulness in carrier service areas that experience T1 noise will be described. As seen therein, T1 noise is not a very big factor at relatively low frequencies (as for example at frequencies below about 600 kHz). However, the magnitude of its interference (cross talk) increases as the frequency increases until it exceeds a level that is acceptable for discrete multi-tone transmission to locations over a mile from a central office. Thus, it is generally agreed that discrete multi-tone transmissions can not be reliably used in subchannels having frequencies above about 600-750 kHz in carrier service areas that experience T1 noise. This is particularly true when the remote locations are located more than about a mile from the source. Thus, T1 noise significantly limits the number of subchannels that are available for data transmission in the forward direction, which severely limits the speed at which digital data can be transmitted as is illustrated by the graph shown in Figure 4. However, as seen in Figure 3, at frequencies above approximately 1.3 MHz, the amount of crosstalk generated by T1 noise begins to decline rather significantly. A second hump in the T1 noise cur begins to become significant above about 1.6 MHz. Therefore, subchannels in the range of about 1.3 to 1.6 MHz tend to be relatively immune from T1 cross talk noise. Accordingly, when the broader 512 subchannel bandwidth described above is used, 6 Mbps data transmission rates can be readily achieved even in the presence of significant T1 crosstalk noise in an adjacent (or even the same) binder.

As will be appreciated by those skilled in the art, this overcomes one of the most frequent criticisms of the discrete multi-tone transmission standard for Asymmetric Digital Subscriber Line service in North America. It should be appreciated that the actual

By way of example, application of the invention in a system that co-exists with amateur radio broadcasts will be described. Figure 7 illustrates the representative bit rate distributions for a discrete multi-tone system described above with reference to Figure 2 with the frequency bands that correspond to amateur radio transmissions are simply masked out. That is, in the embodiment shown, three narrow bands 215, 217 and 219 are simply masked so that the discrete multi-tone system does not transmit in the masked frequency ranged. It should be appreciated that the masking does not significantly alter the system's data transmission capabilities. In the embodiment shown, the masked bands include the 1.81 to 2.0; 3.5 to [illegible]; and 7.0 to 7.1 MHz frequency bands. The same 25.6 Mbit/sec data transmission rate is obtainable with a drop of only approximately one decibel in the margins when compared to the system described above with reference to Figure 2. Such margins are well above the 6 decibel margin generally considered necessary for such data transmission systems.

The described arrangement has several other advantages as well. Most notably, in systems that do not experience crosstalk noise (which is the vast majority of the installed telephone base in North America) significantly higher data transmission rates can be reliably achieved. By way of example, in the bandwidth doubling example presented above, data rates of at least 12 Mbps can be reliably obtained at distances over 6000 feet on twisted pair subscriber lines. Further, when the number of subchannels available for transmission in the reverse direction are also doubled, the potential data transmission rate in the reverse direction can also be significantly improved. By way of example, transmission rate of at least 1.544 Mbps (i.e. the T1 data transmission rate) are readily obtainable.

As will be appreciated by those skilled in the art, the data transfer rates that are obtainable by any given system are a function of a number of variables. Some of the relevant variables include the distance that the signals must travel over the transmission lines, the nature of the transmission lines, the margins required, the transmitter power level, and the attendant noise. Thus, systems where the signals have generally shorter distances

can be used to provide significantly improved data transmission rates using existing infrastructure.

Referring next to Figure 5 a video delivery system that operates in accordance with the present invention will be described. A video server 21 provides digital data to transmitter 20 through an asynchronous transfer modem switch 22. The video server 21 can provide data at any data rate up to the maximum data rate permitted in view of the transmission distance, the line quality and type of communication lines used. The transmitter 20 incorporates several components including an encoder 23 and a discrete multi-tone modulator 25. The encoder 23 serves to multiplex, synchronize, encode and compress the video data and is capable of handling data rates of up to 15 million bits per second. More specifically, it translates incoming bit streams into in phase, in quadrature components for each of a multiplicity of subchannels. The encoding may be done using forward error correction and/or trellis coding. In the embodiment shown, 512 subchannels are available. Therefore, the encoder outputs 512 subsymbols sequences that each represent 4 Kbps. These inputs are complex inputs that are passed to a discrete multi-tone modulator 25. By way of example, a suitable encoder is described in detail in the above referenced ATIS standard.

The modulator 25 is an IFFT modulator that computes the inverse Fourier transform by any suitable algorithm. Since the encoder outputs are complex numbers, the IFFT modulator receives 1024 inputs. The bit distribution is determined adaptively in discrete multi-tone systems as described in the referenced ATIS standard. To facilitate this, the transmitter 20 also includes a line monitor that monitors the communication line to determine the line quality of each of the available subchannels. In one embodiment, the line monitor determines the noise level, signal gain and phase shift on each of the subchannels. The object is to estimate the signal to noise ratio for each of the subchannels. Therefore, other parameters could be monitored as well or in place of the parameters described. The determination of what subchannels to transmit the encoded data over as well as how much

decoder 33 that decodes the demodulated signal. The demodulator 31 and the decoder 33 perform inverse functions of the modulator 25 and encoder 23 respectively. The decoded signal is then passed from the decoder 33 to a remote unit 36 such as a television, a computer, or other suitable receiving apparatus. The function of the time domain equalizer, the demodulator 31 and the decoder 33, as well as algorithms suitable for accomplishing the desired functions are all described in more detail in Chow et al.'s United States : at No. 5,285,474.

The upstream encoding and modulation may be done in exactly the same manner as the described downstream data transmission. However, in the described embodiment, just 64 subchannels are made available to upstream communications. However, it should be appreciated that any number of subchannels could be made available for such upstream communications.

In several of the described embodiments, the subchannel bandwidth has been considered fixed. However, in some applications, it may be desirable to provide a mechanism for dynamically adjusting the bandwidth of the subchannels in unison. In such systems, the data transmission rates obtainable by a fixed number of subchannels may be increased merely by broadening the subchannel bandwidth. For example, one representative system may include 256 subchannels each of which has a bandwidth that may be varied in the range of 4.3125 kHz - 34.5 kHz. Of course, the actual ranges may be widely varied in accordance with the needs of a particular system. In one such arrangement, the system may initially be set up to operate with the subchannels widths each being at the minimum width. Then, as the system's load increases, the subchannel widths may be gradually adjusted as required to handle the increasing data transmission requirements. Typically, the bandwidth increasing step would be taken only infrequently and treated as a system upgrade. In other embodiments, the bandwidth may be dynamically increased and decreased to meet the current data transmission needs of the system.

IN THE CLAIMS:

1. A discrete multi-tone transmitter that is suitable for transmitting digital data over a twisted pair communication line on a multiplicity of subcarriers having different frequencies, the transmitter comprising:

an encoder for encoding digital information, the encoder being capable of encoding digital information at speeds in excess of six megabits per second;

a monitor for monitoring a communication line to determine line quality parameters indicative of noise levels at each of a multiplicity of subchannels, each subchannel corresponding in frequency to an associated subcarrier;

a modulator for modulating the encoded digital information onto a multiplicity of subcarriers in a discrete multi-tone signal, each subcarrier corresponding to an associated tone and an associated subchannel, wherein the available subcarriers for the discrete multi-tone encoded signal have a combined bandwidth of at least 1.6 MHz, the modulation being arranged to take into consideration at least the detected line quality parameters and a permissible power mask parameter, and wherein the modulation is capable of dynamic updating both the subchannels used and the amount of data transmitted on each subchannel during transmission in order to accommodate real time changes in specific parameters; and

an adder for appending a cyclic prefix to the discrete multi-tone signal before it is applied to the transmission line.

2. A transmitter as recited in claim 1 wherein the modulator modulates the encoded digital information onto subcarriers that correspond to subchannels that each have a bandwidth that is in the range of approximately 4.3125 kHz to 34.5 kHz wide.

8. A discrete multi-tone receiver for receiving a first set of multi-tone encoded digital information over a communication line that may take the form of a twisted pair communication line, the receiver comprising:

a demodulator for demodulating the encoded digital information from a multiplicity of subcarriers in a discrete multi-tone signal at data rates in excess of six megabits per second, each subcarrier corresponding to an associated tone and an associated subchannel, wherein the available subcarriers for the discrete multi-tone encoded signal have a combined bandwidth of at least 1.6 MHz, the demodulation being arranged to receive modulation information as part of the discrete multi-tone signal, wherein the demodulator is capable of dynamic updating during reception in response to changed modulation information in order to accommodate real time changes in the modulation scheme, the demodulator being arranged to strip the cyclic prefix from the discrete multi-tone signal;

a decoder for decoding the demodulated digital information in real time;

an encoder for encoding a second set of digital information; and

a modulator for modulating the encoded second set of digital information onto a multiplicity of subcarriers in a second discrete multi-tone signal, each subcarrier in the second discrete multi-tone signal corresponding to an associated tone and an associated subchannel, wherein the available subcarriers for the second discrete multi-tone encoded signal have a combined bandwidth that is significantly less than the bandwidth of the subcarriers that are available to the first discrete multi-tone encoded signal.

9. A receiver as recited in claim 8 wherein the second discrete multi-tone encoded signal has up to sixty four separate subcarriers and is transmitted over the communication line to a source.

12. A method as recited in claim 11 further comprising the steps of receiving the signal at the remote location and demodulating and decoding the signal received at the remote location.

13. A method as recited in claim 1 wherein the tones each have a bandwidth that is at least approximately 4.3125 kHz wide.

14. A method as recited in claim 13 wherein up to 512 tones may be utilized to facilitate the use of a bandwidth of at least approximately 2.208 MHz.

15. A method as recited in one of claims 11 and 14 wherein the multi-tone encoding is done in substantial compliance with the ATIS Asymmetric Digital Subscriber Lines standard and wherein the subchannels that occur at frequencies above those set forth in the standard are treated similarly to those within the standard range in terms of subcarrier selection criteria.

16. A method as recited in claim 11 wherein when significant noise or interference is detected during said monitoring step, the modulator is arranged to transmit the data at frequencies above and below the most significant noise or interference to facilitate transmission of the encoded digital data throughout a carrier service area.

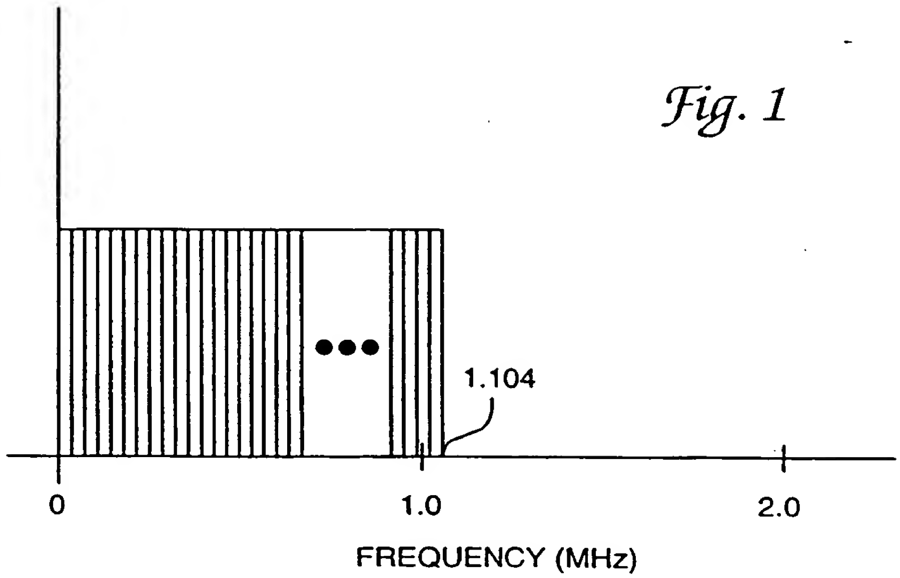


Fig. 1

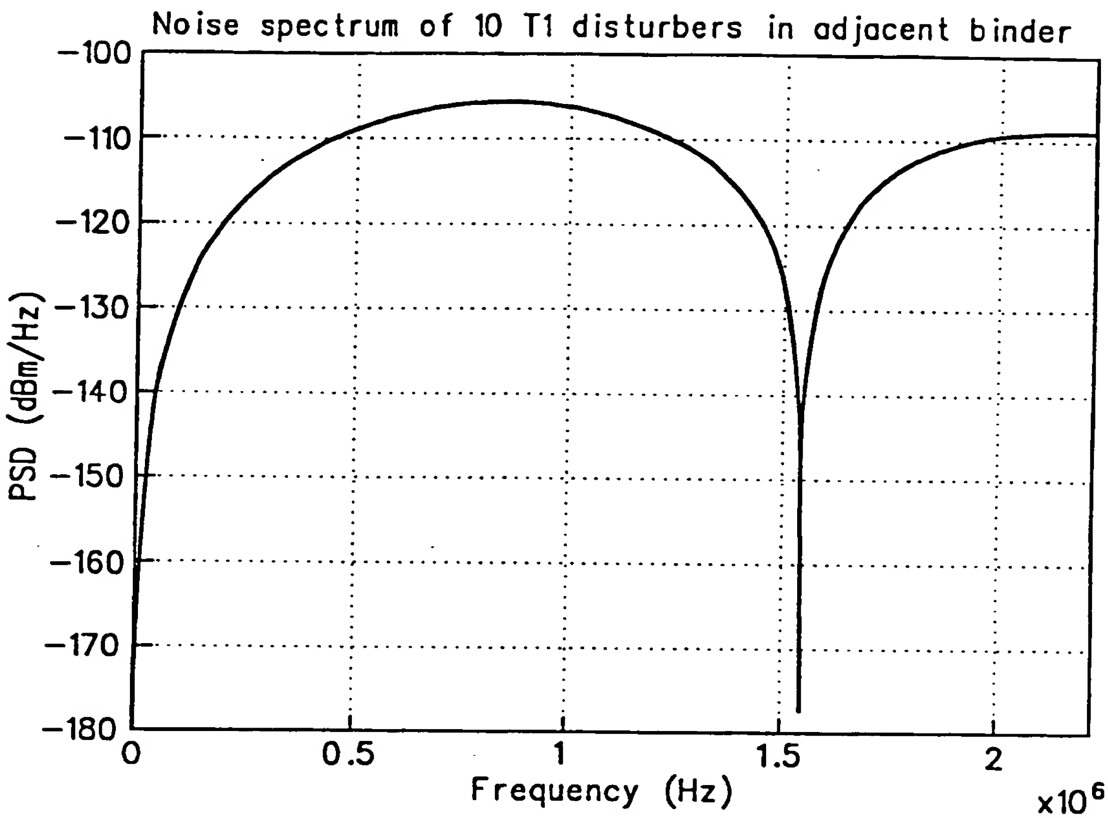

Noise spectrum of 10 T1 disturbers in adjacent binder
−100
−110
−120
−130
−140
−150
−160
−170
−180
PSD (dBm/Hz)
0
0.5
1
1.5
2
Frequency (Hz)
x10^6

Fig. 3

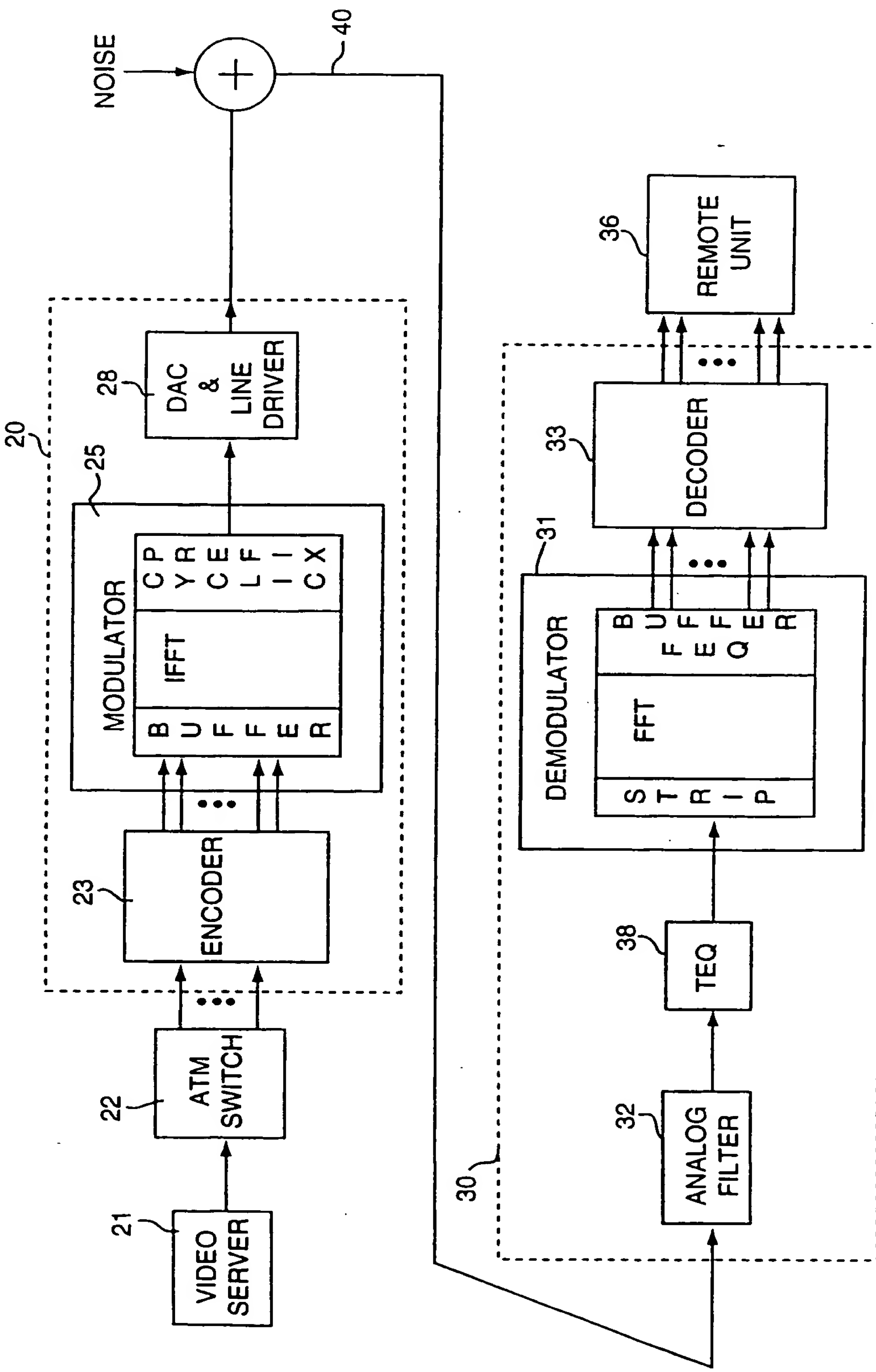

NOISE
40
20
25
28
DAC & LINE DRIVER
MODULATOR
BUFFER
IFFT
CYCLIC PREFIX
23
ENCODER
22
ATM SWITCH
21
VIDEO SERVER
36
REMOTE UNIT
33
DECODER
31
DEMODULATOR
STRIP
FFT
BUFFEQ
FEQ
38
TEQ
32
ANALOG FILTER
30

Fig. 5

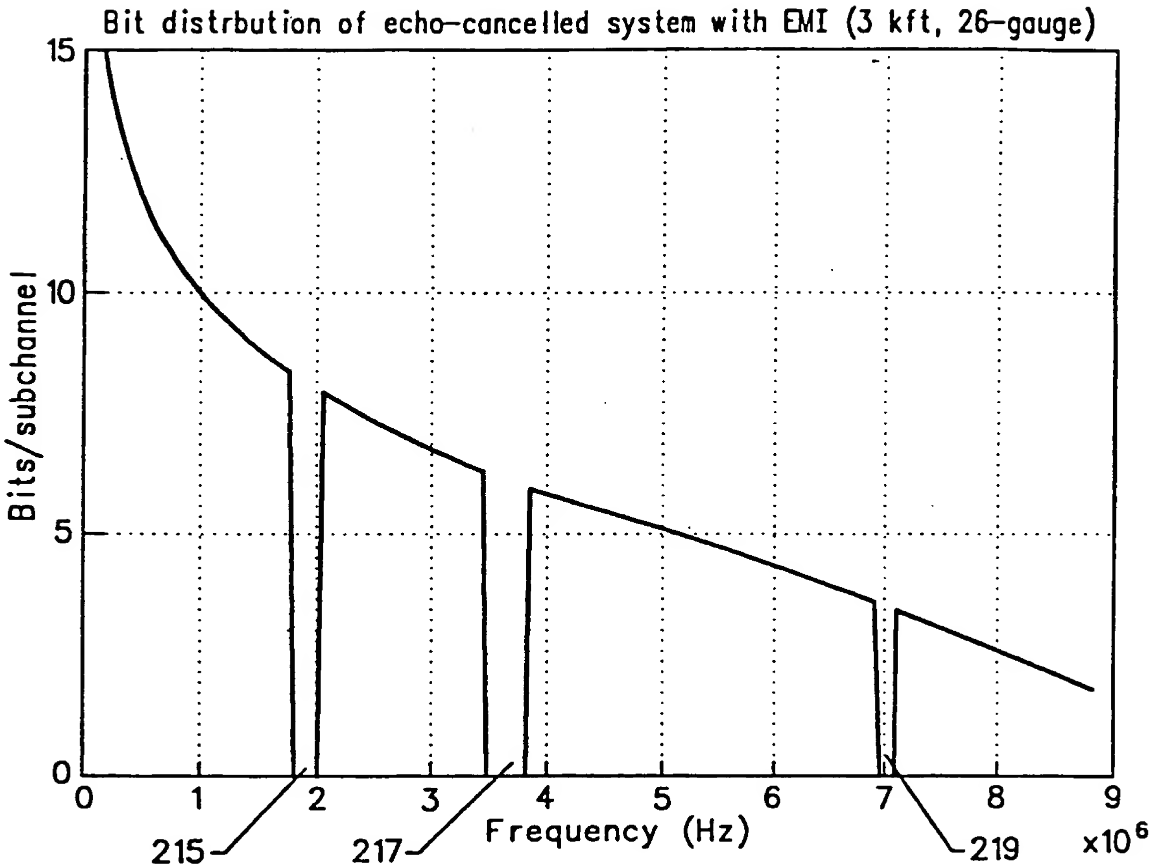

Bit distrbution of echo-cancelled system with EMI (3 kft, 26-gauge)
Bits/subchannel
15
10
5
0
0
1
2
3
4
5
6
7
8
9
Frequency (Hz)
x10^6
215
217
219

Fig. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US95/04809

A. CLASSIFICATION OF SUBJECT MATTER:
IPC (6):

H04B 1/06, 1/10, 1/66, 7/00, 15/00; H04D 1/06; H04J 1/02, 3/00, 13/24, 14/00; H04M 11/00

A. CLASSIFICATION OF SUBJECT MATTER:
US CL :

370/6, 70, 94.1; 375/240, 285, 296, 340, 348, 349; 379/93; 455/266